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# Cost Effectiveness Analysis Using Fuzzy Set Theory

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# 1. Introduction

This report considers decision problems that arise in cost effectiveness evaluations of the nuclear hardening of weapon systems. The decisionmaker typically is asked to evaluate a number of options that involve modifications of the nuclear survivability of some elements of a weapon system, corresponding cost change estimates, and associated changes of other properties of the system. The objective in this problem is to identify options that achieve a high nuclear hardness of the system (i.e., a survivability near unity) with the fewest adverse effects. Hence, the decisionmaker has two goals: to maximize the survivability and to minimize the adverse effects. Usually, these goals are contradictory, creating a classical optimization problem in which the solution depends on the weights that are assigned to each goal. In the case of nuclear hardening, these goals and their weights are not well defined, and the relative importance of each goal can be different for different systems. Similarly, the inputs that define the problem, that is, the amounts of hardening or softening and the corresponding costs and adverse effects, often are known only approximately. These uncertainties typically are not random but are caused by a lack of exact knowledge, and their effect is that the solutions do not define a single best option. Instead, there might be several options with similar effects and comparable costs, and the decisionmaker must choose among these. Actually, this situation is desirable, because it gives the decisionmaker flexibility for his final decision, so that he can take into account constraints that exist but cannot be easily defined in mathematical terms. The described situation, in which the goals and constraints of an optimization problem are only approximately defined and approximate solutions are sought, can be handled by expert systems that use fuzzy set theory for those parts of the problem that are not exactly known. This report outlines principles for the development of such an expert system.

Section 2 discusses the data that are needed to formulate the problem. Section 3 gives a short description of some concepts of fuzzy set theory that are relevant to the present exposition, and section 4 gives an overview of the proposed rule-based expert system. To assist the decisionmaker in generating input for the expert system, we have developed a computer program that analyzes proposed changes in weapon systems. Section 5 contains a short description of that program. A summary and conclusions are given in section 6.

## 2. Data Bank and Case Specification

In this report, the data that define the optimization problem are arranged into two groups: a data base that is available from a data bank and describes the present properties of the system, and a case input that describes the proposed modifications. We assume that a data bank containing nuclear survivability data and cost estimates of weapon systems in the Army inventory is available or can be generated for the purpose of a cost and operational effectiveness analysis (COEA). The nuclear environment that constitutes the threat in nuclear survivability studies is described by the 16 environmental parameters given in list 1. The data bank must contain, for the system being investigated, information about the response of the system to each environmental parameter. This information should generally consist of 16 response functions that describe the dependence of the survivability of the system on the environment. In special cases, survivability values instead of functions may suffice, but this would impair the generality of the COEA investigations. In addition to the response characteristics, the data bank should contain information about the costs of the system and about any other relevant properties, such as delivery time, operational restrictions, etc.

The case specification for a cost analysis defines the environment and describes projected changes of the weapon system being investigated. It contains the following data:

- (1) *Definition of the environment, that is, values of the 16 environmental parameters.* These values can be either exact or approximate numbers, or they can define ranges of interest for the parameters. This input defines the environment for which the investigation should be conducted.
- (2) *Proposed changes of the system's survivability with respect to all relevant environmental parameters.* (Some systems may be insensitive to a subset of the environmental parameters.) A projected modification typically involves a hardening of the system. However, the expert system should be able to analyze nuclear softening with associated cost savings.

**List 1. Environmental parameters.**

1. Overpressure peak	9. Total dose, silicon
2. Overpressure impulse	10. Total neutron dose
3. Dynamic-pressure peak	11. Neutron fluence
4. Dynamic-pressure impulse	12. Total gamma dose
5. Under-pressure peak	13. Minimum threat yield
6. Total thermal energy	14. Maximum threat yield
7. Maximum irradiance	15. Exo-atmospheric EMP
8. Total dose, tissue	16. Endo-atmospheric EMP

- (3) *Costs of the proposed changes.* These costs can denote increases as well as savings; i.e., this input can be positive as well as negative.
- (4) *Other relevant effects of the proposed changes.*

We expect that some of the information will be known only approximately, for instance, during an early exploration of potential system improvements. Thus, the anticipated survivability increase by a projected modification might be characterized as “marginal” and the corresponding cost change as a “small increase.” Linguistic information such as in these examples can be analyzed using fuzzy set theory [1–3]. Of course, a consensus must exist about the meanings of the linguistic labels. The next section describes how these meanings can be uniquely defined for the present problem with the help of fuzzy sets.

Another source of uncertainty is the aforementioned formulation of goals and assignment of weights to the contradicting goals of system design: the increase of survivability and the minimization of costs and adverse effects. Optimization problems with approximately defined data and goals can be treated with the help of fuzzy set theory, by using fuzzy expressions to describe the data, goals, and constraints, and by using fuzzy logic to formulate the rules in the expert system. Because of the vagueness in the definition of the problem, we want the expert system to present the decisionmaker with a commented list of best solutions, thus allowing him to consider, for the final choice, factors that are not explicitly included in the case specification.

### 3. Concepts of Fuzzy Set Theory

The concept of fuzzy sets was introduced by Zadeh [1] to handle imprecise information and poorly definable possibilities of events. Sometimes, judgment is required on the part of the analyst to describe that which is more or less true concerning test measurements, or that which is not possibly sufficient regarding survivability of people and materiel in a nuclear environment. The fuzzy set theory provides a workable numerical method to handle such imprecision.

As an example, consider the characterization of the survivability of a weapon system in terms of linguistic categories. Survivability is measured on a scale from zero to unity, zero meaning that the object does not survive and unity meaning that the object is not affected. Hence, one might agree that a "poor" survivability corresponds to a survivability value of <about 0.2>. In terms of fuzzy sets, the meaning of the concept <about 0.2> is defined by assigning to each survivability value in the vicinity of 0.2 a membership value that indicates to what degree the survivability value belongs to the set <about 0.2>. Usually, these grades of membership, also called membership values, are normalized to a scale from zero to unity, zero meaning no membership and unity meaning perfect membership. The correspondence between survivabilities that belong to the set <about 0.2> and their membership values can be expressed, for example, by a list as shown in table 1. The first column in the table contains survivability values and the second column lists the corresponding grades of membership or membership values. For instance, the survivability value 0.150 belongs to the set <about 0.2>, with a grade of 0.50.

The correspondence between survivability values and membership values can be expressed not only by discrete lists, but also by continuous functions called membership functions. We now present examples of continuous

Table 1. Fuzzy set  
<about 0.2>.

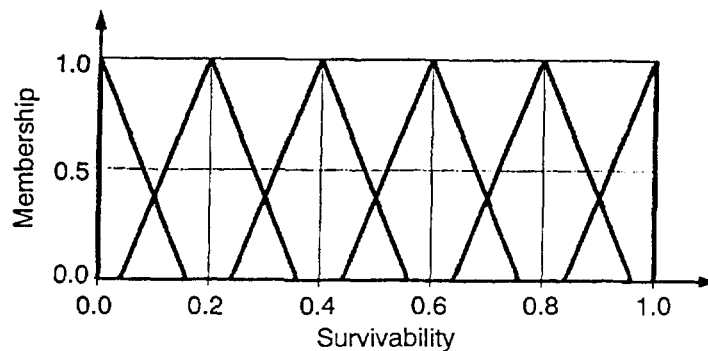
Survivability values	Grades of membership
0.100	0.00
0.125	0.25
0.150	0.50
0.175	0.75
0.200	1.00
0.225	0.75
0.250	0.50
0.275	0.25
0.300	0.00

membership functions. Table 2 lists names of survivability categories that might be used for a linguistic characterization of survivability and the corresponding approximate survivability values. Figure 1 displays overlapping triangular membership functions that we propose for these categories. The overlapping of the membership functions means that the same survivability value can belong to different survivability categories. For instance, the survivability 0.33 belongs not only to the category <about 0.4>, or moderate survivability, but also to the category <about 0.2>, or poor survivability, albeit with a smaller membership value. Such overlapping of sets that belong to different categories renders the boundaries between categories indistinct, thus making fuzzy sets better models of linguistically labeled categories than bins with sharp borders would be. The forms of the membership functions are arbitrary in principle, but triangular or trapezoidal membership functions are common in applications. We arbitrarily chose six survivability categories. Experiments with the categorization of objects indicate that the maximum number of categories for consistent ranking by human judgment is not greater than ten, and about six is felt to be a convenient number. The categories in table 2 and the membership functions in figure 1 are proposed as a working example. In a final expert system, the user should be able to enter his own survivability categories and membership functions. Then, in any particular application, the number of categories and the forms of their membership functions could be defined by consensus among the users of the expert system.

**Table 2. Survivability categories.**

Survivability category	Survivability value
Very poor	about 0.0
Poor	about 0.2
Moderate	about 0.4
Quite good	about 0.6
Good	about 0.8
Very good	about 1.0

**Figure 1. Memberships of survivability categories.**



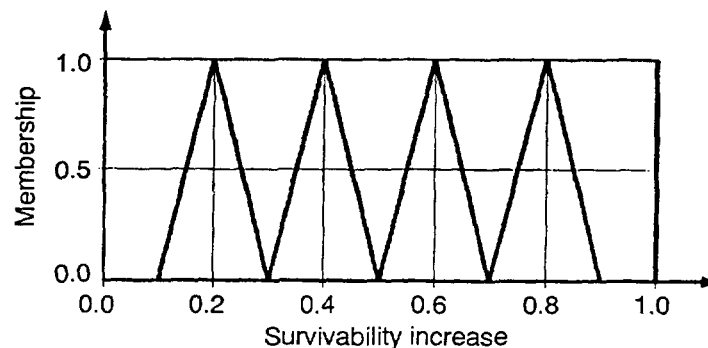
The survivability of a weapon system, in general, does not exactly match any of the categories in table 2. Therefore, the expert system must also be able to handle other data types. In particular, the expert system should accept as definitions of survivability crisp (exact number) data, data defined by the categories, more general approximate characterizations such as "quite good" to "good," and arbitrary fuzzy sets.

In addition to the survivability itself, the expert system needs the specifications of planned survivability changes. Again, we allow three types of input: linguistic information, fuzzy sets, and exact numbers. Because the survivability can assume only values between zero and unity, its changes are restricted to the interval  $[-1, +1]$ . Table 3 lists linguistic categories of survivability and their corresponding approximate survivability values, and figure 2 shows the corresponding membership functions for the positive changes. The survivability-change categories are consistent with the survivability categories of table 2 in the sense that a "small" change shifts a given survivability category up or down to the next category. The decrease of sur-

Table 3. Categories of survivability changes.

Survivability-change category	Value of survivability-change
Negative large	-1
Negative large medium	about -0.8
Negative medium	about -0.6
Negative small medium	about -0.4
Negative small	about -0.2
No change	0
Positive small	about 0.2
Positive small medium	about 0.4
Positive medium	about 0.6
Positive large medium	about 0.8
Positive large	+1

Figure 2.  
Memberships of  
hardening categories.



vivability (softening) is modeled by functions similar to those of figure 2, but on the negative axis of the change. The survivability-change categories, <negative large>, <no change>, and <positive large>, are assumed to be crisp numbers with the values  $-1$ ,  $0$ , and  $+1$ , respectively.

Two other measures that might be applicable to the evaluation of nuclear hardening proposals are the hardening rate and the unit price of hardening. Hardening rate is the ratio of survivability change to the costs of the change, and the unit price of hardening is the inverse of the hardening rate. The computation of these quantities from approximate data presents interesting fuzzy arithmetic problems. The results are fuzzy numbers for which a ranking algorithm must be devised. (The ranking of fuzzy numbers is not unique, and ranking algorithms that are appropriate for any particular application may be selected from published algorithms or constructed anew.) However, it is doubtful that these measures alone are of much use for nuclear hardening cost analysis problems because the proper criteria in these problems are not purely commercial, but include other factors that affect the performance of the system.

Examples of factors that can be important for the selection of best options are the time necessary to implement suggested hardening, changes in the operability of the system, compatibility between modified and original systems, etc. Such factors, if they cannot be assigned exact numbers, often can be quantified with the help of linguistic labels or in terms of membership functions.

## 4. Rule Basing of the Expert System

The purpose of the expert system for a COEA is to help a decisionmaker to sort and rank various modification options of a weapon system. The decisionmaker presents a list of options to the expert system, and receives from it recommendations for the ranking of the options. The expert system may take into account any factors that are deemed important, such as the achieved survivability, costs, time needed for the implementation of the changes, effects on the operability of the system, durability of the modified system in comparison with the original system, etc.

Rules in an expert system usually have the form

IF  $A = B$ , THEN  $C = D$ .

In the present application, the variables  $A$ ,  $B$ ,  $C$ , and  $D$  can contain representations by fuzzy sets or linguistic categories. A typical rule might have, for instance, the following form

IF *the achieved survivability is high*, THEN *implement the change*.

In general, the achieved survivability is a fuzzy set (because some of the input information is likely vague). Similarly, the category “high survivability” is a fuzzy set. Therefore, the equality relation in the antecedent of the rule involves a comparison of two fuzzy sets. One expects from the expert system that, given this rule, it will determine to what extent the survivabilities of different proposed options approximate a “high survivability” and the expert system will rank the options accordingly. This problem can be efficiently handled by fuzzy expert systems.

In reality, the expert system will contain many more rules; for instance:

IF *the implementation time is long*, THEN *do not implement the change*.

or

IF *the performance improves*, THEN *implement the change*.

Several rules may contradict the mutual prescription, and a compromise solution must be sought and proposed to the decisionmaker. The finding of compromise solutions is one of the strengths of expert systems that use fuzzy set theory.

To construct a rule-based expert system that involves fuzzy information, one can use commercially available fuzzy programming tools that in essence are programming languages specifically designed for such tasks. Alternatively, one can use expert systems, or so-called inference engines, that are programmed in common languages such as Pascal, Fortran, or C. An important factor in deciding on the programming tool or language is the portability of the final product. Examples of recent literature about fuzzy expert systems are Kandel [4] and Terano et al [5].

## 5. Auxiliary Program Scap

The expert system described in the previous section uses as input, among other information, the survivability of the weapon system being investigated and the changes in the survivability. Often, the contemplated changes affect only some elements of the system. For instance, an armored vehicle might be modified by replacing its communication system with a hardened version. In general, one needs to determine how a replacement of some elements affects the survivability of the whole system. The calculation of the system survivability from the survivabilities of its elements is the subject of a recently developed computer program, Scap [6].

The program Scap analyzes the survivability of a weapon system that is specified in terms of several interdependent elements. The interdependencies are expressed in the form of a logical fault tree, and the descriptions of the elements are stored in a file that represents the data bank described in section 2. The program is activated by presenting to it the case input, that is, a list of proposed changes of some element survivabilities and cost estimates of the changes. The survivabilities of the original elements, as well as the proposed changes of their survivabilities, can be either exact (crisp) numbers or linguistic descriptions as outlined in section 3, or they can be in the form of fuzzy sets. The calculations within the program are based on fuzzy arithmetic and fuzzy logic.

The program computes the system survivability, with respect to each of the 16 environmental parameters, before the changes, and for all combinations of proposed changes after their implementation. The user can indicate which survivability is relevant for his analysis: the system survivability, with respect to all 16 environmental parameters or with respect to a specified subset of the parameters. The program calculates the user-defined relevant survivabilities for all options (all combinations of proposed changes) and presents to the user a list of five options that achieve the highest levels of the relevant survivability. Options with comparable relevant survivability values are ordered according to their costs. The survivability values of the elements, as well as those of the system, are represented within the program and in the output by fuzzy sets. To facilitate the use of these results, the fuzzy numbers of the results are interpreted in linguistic terms with the help of the categories described in section 3.

We expect to use the output of Scap as input for the planned expert system for the COEA. In fact, if only the relevant survivability and costs are important, then the output of Scap already contains the information that can be expected from an expert system. If, however, other factors are important, then a general expert system is necessary, because such factors can change the simple ranking that is provided by Scap and based only on the achieved survivability and costs.

## 6. Summary and Conclusions

This report considers the task of developing an expert system that provides support to a COEA of nuclear hardening of weapon systems. In particular, the contemplated expert system is expected to analyze proposed modifications of the weapon system, such as hardening or softening of some elements of the system, with associated costs, changes in operational capabilities, time of implementation, etc. For most—if not all—such modifications of systems, no exact algorithms and quantitative descriptions are available to assess their benefits. Instead, rules might be postulated that are based on the experience of experts in the field, and combined into a system of rules, or inference engine. We expect the rule-based expert system to advise the decisionmaker about the benefits of various proposed changes of the weapon system by presenting a list of best options with explanations about the reasons for the choices.

The primary data for the analysis are the survivability values of the weapon system with respect to 16 environmental parameters that describe the nuclear threat. These values are not necessarily exact, particularly when hypothetical changes of the weapon system are analyzed. Therefore, the expert system should allow input not only in the form of exact data but also in the form of linguistic descriptors, such as “large” or “small.” Because linguistically specified data can be rationally analyzed with the help of fuzzy set theory, we intend to represent such data in the expert system by fuzzy sets. This representation also allows one to accommodate approximate rules, such as “*IF the costs are small, THEN update the system.*”

The relevant survivabilities of the modified weapon system that are calculated by the expert system are given in the form of fuzzy sets. To facilitate the use of the results, these survivabilities will be translated into linguistic terms.

To test the concept of the expert system and the usefulness of fuzzy set representation, we have developed an auxiliary program, Scap, that analyzes weapon systems composed of interactive elements. The program investigates the consequences of proposed changes of the survivabilities of elements of the system and makes a list of best options in terms of system survivability. The program is equivalent to an expert system in the special case when only survivability and costs are important. If other factors (implementation time, operability, etc) are also important, then the output of Scap is but one input to a more elaborate expert system.

We conclude from numerical experiments with Scap that a rule-based expert system for COEA of weapon systems can be a useful tool for the decisionmaker. Inherent inaccuracies in the data and in decision rules can be modelled with the aid of fuzzy set theory.

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